

## **Final Report on Organic Materials Ionizing Radiation Susceptibility for 55 We Stirling Convertor**

The DOE is considering the current STC 55 We Stirling Technology Demonstration Convertor (TDC) as a baseline option for an advanced radioisotope power source for the Outer Planets/Solar Probe project of JPL and other missions. However, since the TDC contains organic materials chosen without any special consideration of flight readiness, and without any consideration of the extremely high radiation environment of Europa, a preliminary investigation was performed to address the radiation susceptibility of the current organic materials used in the TDC.

This report documents the results of the investigation. Section 1 contains a brief executive summary. Section 2 contains the final presentation charts to DOE. Sections 3 through 10 discuss each organic material that is a component in the 55 We TDC. Section 11 contains a summary recommendation. Section 12 lists valuable references needed to support conclusions in this report. Section 13 contains data sheets, ancillary information for current and replacement materials, and excerpts from some of the references in Section 12.

### **1. Executive Summary: Stirling Convertor Organic Materials Ionizing Radiation Survivability**

The following executive summary was presented January 28, 2000 at a NASA headquarters meeting to review the overall Stirling readiness. No new conclusions or substantially new information exists since the time of this executive summary. However, sections 4 through 10 of this report do give more complete information on each of the organic materials.

#### ***Organic Materials Ionizing Radiation Survivability Study by GRC et al***

The mission to Europa imposes a very severe ionizing radiation environment to the 55-We TDC. The radiation from the isotope power source is insignificant when compared to radiation from the environment for 30 days in the Europa orbit. The alternator magnets and organic materials capabilities to meet these requirements were initially unknown. As it turns out, the magnets meet the requirements, and data from literature shows practically no degradation at the expected dose. However, the 55-We TDC's built to date contain some organic materials which will not survive the harsh Europa environment. A detailed assessment has shown that acceptable substitute materials exist for the organics. An effort was made to choose substitute materials close to the same family and function as the original. These were evaluated by STC and thought to be acceptable for future TDC's. Should unexpected problems arise with the substitutes, and a second substitute must be made, there is a sufficient list of candidate radiation tolerant organic materials from which to choose.

All of the organic materials are sealed inside the pressure vessel and cannot escape to contaminate the rest of the spacecraft and therefore outgassing should not be a problem. The pressure of the helium inside the vessel should also act to inhibit outgassing from the

organic materials. The coldest part of the Converter is the pressure vessel, therefore any outgassed organic material would deposit on this wall and should in no way affect the function of the converter.

NASA Glenn through consultation with members of the JPL staff, with Lockheed Martin in Valley Forge, PA, with GE-Schenectady, NY, the STC, and commercial material vendors has carried out this evaluation. Additional coordination with the JPL Europa spacecraft materials engineers is expected as the decision to consider using Stirling for a radioisotope power system(RPS) is finalized. Further confirmation of functional suitability of the new materials will come in the following months as two 55-We TDC's (S/N 005 and 006) will be built with these new materials to the maximum extent possible. These TDC's are scheduled for delivery and testing at NASA GRC in mid-2000.

## **2. Presentation Final Update of January 11, 2000.**

The following presentation contains summary information on requirements, a listing of each material, and how the problem was resolved for each material as of January 11, 2000. Some new or more complete information is given in sections 4 through 10.

### **Stirling Power System for Europa Radiation Environment**

#### **Key Issue:**

**Radiation tolerance of organic materials inside Stirling converter;  
Radiation tolerance of NdFeB permanent magnets.**

#### **Approach:**

- 1) Collect information from a variety of sources: literature, vendor information, radiation experts, space materials experts, and lubrication experts.**
- 2) Estimate expected total ionizing dose inside the converter.**
- 3) Choose alternate materials for flight article as warranted.**

#### **Summary:**

**Revised organic materials and NdFeB magnets will survive the Europa radiation environment with margin.**

## Stirling Power System for Europa Radiation Environment

### Activity/Schedule

#### Task 6 - Radiation Effects

Identify Suspect Materials October 7 Complete  
 NdFeB Radiation Assessment by LMA November 3 Complete  
 Define Candidate Replacements November 19 Complete  
 Assessment Complete December 10 Complete

### RADIATION SURVIVABILITY STATUS:

- Organic Materials Radiation (GRC, others) **Updated as of January 11, 2000**

Candidate replacement materials have been identified which appear to be acceptable in the harsh Europa radiation environment.

- NdFeB Magnet Assessment (Lockheed Martin) **December 16, 1999**  
 LMA has concluded that the Europa radiation environment will produce insignificant changes in the Nd-Fe-B magnetic materials.

## Stirling Power System for Europa Radiation Environment

### RADIATION SURVIVABILITY REQUIREMENT:

“The total ionizing dose from the *natural space environment* (Europa Orbiter Mission 01) is estimated to be  
 10 MRAD (Si) with a 50-mil aluminum housing for shielding;”  
 4 MRAD with 100 mil shielding.

Old Material	Location	Purpose	New Material/ Mission Rating
Xylan 1620-560 Blue	Piston OD	Bearing Coating	Xylan 1054 <b>1</b>
Polyimide (Kapton)	Wire Insulation	Wire Insulation	Acceptable as is <b>1</b>
Dolph CB-1057 Epoxy	Coils	Bonding Agent	EC2216 <b>1</b>
Loctite 420	Stator laminations	Wicking Adhesive	Loctite 4014 or Epotek 301 <b>2</b>
Scotch-weld DP-460	Magnets, Stator	Epoxy Adhesive	EC2216 <b>1</b>
3M heat shrink tubing	Wire connectors	Electrical Insulation	Raychem PVDF <b>1</b>
Kapton tape (KA00)	Edge of Stator	Electrical Wire Protection	Permacel or 3M Y966 <b>1</b>
Garolite G-10	Coils, Laminates	Electrical Insulation	Acceptable as is <b>1</b>
TFE Insulation	Wires for Feed Through	Electrical Insulation	Raychem PVDF <b>1</b>
TFE Structure	End of Piston	Power Piston Bumper	PVDF or ETFE machined <b>1</b>

#### \*Mission Rating:

1 = Current materials acceptable  
 2 = Acceptable; requires dose calculations  
 3 = Acceptable, with dose calculations & test data  
 4 = Questionable; conclusive proof required  
 5 = Unacceptable

#### Conclusions:

- **Candidate replacement organic materials have been identified which appear to be acceptable in the harsh Europa radiation environment.**

## Stirling Power System for Europa Radiation Environment

**Xylan 1620-560 blue** is a Teflon-based lubricant coating. Teflon cannot survive in the Europa radiation environment. Can be replaced by Xylan #1054, which is a MoS<sub>2</sub>-based coating. STC has experience with Xylan coatings, so staying within same family of lubricants is low-risk. High pressure dry helium environment will negate any worries of MoS<sub>2</sub> humidity and water vulnerability. STC has 1054 on order and will investigate for suitability. Reference: recommendation memorandum dated 11/18/99 from Steve Pepper to Richard Shaltens.

**Polyimide (Kapton)** wire insulation does not need to be replaced. Radiation tolerance of Kapton is excellent. Shows no degradation until about 400 MRADS. This will be used on the square wire in the magnet windings, "Polyimide-ML".

**Dolph CB-1057 Epoxy** used on the windings will be replaced with 3M-EC2216. JPL identifies 3M-EC2216 as a typical spacecraft adhesive good to 1E+08 RADs or better.

**Loctite 420** can be replaced with Loctite 4014; almost same adhesive, but with test data for radiation hardness. 4014 retains 83% of shear strength after exposure to 7 megarads. However, Chuck Baumgartner of GE recommends Epotek 301, which has been tested at GE to 3 MRAD with no degradation, and can survive higher doses per NASA-CR-1781 general information for epoxies.

**Scotch-weld DP-460** adhesive on the stator magnets. According to 3M, a good substitute is 3M-EC2216. This is used in the terrestrial nuclear power industry. Also, STC has received a small sample and it looks acceptable. STC has used this recently in assembling some stator magnets.

## Stirling Power System for Europa Radiation Environment

**3M heat shrink tubing** used around the wire connectors. Wire insulation, in general, could be Crosslinked PVDF and ETFE insulation; both pass 500 MRADS. Raychem to send samples. There are other possible vendors. Difficult to get small quantities with certifications for flight.

**Kapton Tape (KA00)** Kapton portion is acceptable. Several sources are available for flight-qualified Kapton tape. Adhesive used must be Y966 or better flight-qualified. JPL uses Permacel product; stored in 3M 2100 shielding bags for contamination protection.

**Garolite G-10.** G-10 is not a problem at 4 MRAD.

**TFE Wire insulation** for general wire insulation is not acceptable. JPL recommends replacement with Crosslinked PVDF or ETFE. Best insulation is JPL custom ST-119xx series cabling, Kapton wrapped. Difficult to get small quantities with certifications for flight.

**TFE Structure** is unacceptable (piston bumper). STC will replace TFE with PVDF or ETFE. STC has ordered and received bar form; looks acceptable; will machine as a bumper on the piston end.

### 3. Final Report on Xylan Lubrication

Xylan is used as a lubricant on the outer diameter of the piston. Although there is no contact during nominal operation, the Xylan is needed to facilitate components/parts installation in the build-up process and to ensure no metal-to-metal contact during non-operating and launch vehicle ascent conditions. There was an extensive investigation of a replacement for the original Xylan-blue, since the original contained Teflon, a material

which cannot withstand the 4 MRAD expected dose. Teflon is notably very poor in even low-level ionizing radiation environments. A type of Xylan that uses Molybdenum disulfide as the active lubricant component was selected as a replacement. Since the components of this type of Xylan are very radiation resistant, it follows that the Xylan itself is rad-hard. No radiation testing data is available on the chosen Xylan.

The following report was made on December 18, 1999, and there is no new information:

11/18/99

Subject: Substitute Piston Lubricant for STC Space Stirling Engine

The interior of the 55 W Stirling engine that is proposed for the Europa mission will be subjected to an ionizing radiation dose of about 4 Mrads (Si) during the mission. The lubricant on the engine's piston must survive this dose. The present lubricant is not a satisfactory choice for this service condition and a substitute must be found. A substitute is recommended in this memo.

*Background.* The present lubricant is Xylan 1620-560 (blue) manufactured by Whitford Corporation, West Chester, PA. The active lubricant in this product is PTFE (polytetrafluoroethylene, teflon) and this PTFE is, according to Brian Willis of Whitford (610-296-3200, x232), held in a polyamide-imide resin binder. According to Ron Olan of STC (509-735-4700, x108), the piston lubricant is present to protect the piston and cylinder wall during handling, assembly and initial operation (run-in). It is also expected to be protective during the vibration of launch and other initial vehicle maneuvers. It is not expected to be operational past this point, since the engine is designed for a piston-cylinder wall clearance of .001" during normal operation, during which there is no contact of the piston with the cylinder wall. Although these service requirements on the piston lubricant appear to be very mild, the radiation environment is very severe on the PTFE and results in undesirable emission of gaseous fluorocarbon breakdown products and embrittlement of the PTFE. Such embrittlement may result in the formation of a wear particle that could be caught between the piston and cylinder wall and jam the engine, a catastrophic event. Thus a lubricant such as the one presently used should be avoided and a recommendation should be made for a substitute that is not as vulnerable to ionizing radiation.

*Recommendation.* This recommendation is motivated by the wish to retain the positive experience that STC has had with the Xylan product they have used up to the present. The 1620-560 is really one of a family of products, all going by the generic name of Xylan, but formulated with different active lubricants in the binder. Xylan 1054 is identified here as a radiation-resistant substitute for the present lubricant. This product uses MoS<sub>2</sub> (Molybdenum Disulfide) powder lubricant formulated in the polyamide-imide resin binder. MoS<sub>2</sub> is an inorganic mineral that is *invulnerable* to ionizing radiation. It is also noted that the helium environment in the engine is an ideal environment for the tribological application of MoS<sub>2</sub>, which does not perform well in either moisture or oxygen. The binder, however, is still an organic material that merits some comment. According to Brian Willis, the 500°F cure that the neat polyamide-imide resin undergoes during its application on the workpiece converts it entirely to polyimide. Polyimide is extremely resistant to ionizing radiation. According to "Radiation Design Handbook, Sec.III (Electrical Insulation Materials and Capacitors), by C. L. Hanks and D. J. Hamman, NASA CR-1787, July 1971", polyimide retains its properties up to a dose of 100 Mrads. In addition, the polyamide-imide is a good tribological material in its own right and is marketed for this purpose by BPAmoco under the name of Torlon. Quoting from the BPAmoco website:

<http://www.bpamocochemicals.com/products/product.asp?productid=57&refobj=3&refid=129>,

#### Torlon (Polyamide-imide)

Torlon® polyamide-imide provides exceptional strength at high temperatures, excellent resistance to creep and wear plus the benefits of injection mouldability. The material has unmatched friction-wear characteristics in the most severe service environments.

Typical applications for Torlon polyamide-imide include chemical processing equipment, bearings and seals, automotive/aviation components, electrical/electronic devices, rotating machinery, oil drilling equipment, and industrial equipment.

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The BPAmoco design handbook [Stacey McNeil, BPAmoco (404-346-8242)] also indicates radiation resistance up to at least 10 Mrads.

*Conclusion.* Xylan 1054 is recommended as a radiation-resistant substitute for the Xylan 1620/560 presently in use. These considerations have been communicated to Ron Olan of STC and they are in the process of acquiring Xylan 1054 to try it out. In addition, the Surface Science and Tribology Branch 5140 has a calibrated facility to x-ray irradiate materials. Irradiation and subsequent tribological testing of films prepared by STC may be considered in the future to provide additional confidence in the survivability of Xylan 1054 under irradiation.

#### **4. Polyimide (Kapton)**

Kapton is used as wire insulation. It shows only incipient to mild damage below  $10^8$  Rads according to page 9 of reference 1. Our dose is less than  $4 \times 10^6$  Rads as listed in on page 152 of Reference 2.

#### **5. Loctite 4014 to replace Loctite 420**

Loctite 420 was used as a wicking adhesive to bond the stator laminations together. The laminations are a stack of Hiperco 50 plates. The plates are put in a moist oven to form an oxide layer. The oxide layer acts as an electrical insulator. The mover laminations are bolted to the moving rod. These laminations interact with the magnetic field and cause a current to flow in the stationary coils. The viscosity of the uncured Loctite 420 is around 1 to 5 centipoise (1 cp is typical for water). The low viscosity is needed so that the adhesive will “wick” in between the sandwich layers, after the sandwich is assembled. Loctite technical representative gave a substitute of 4014 when asked about a similar adhesive to 420 suitable for a radiation environment. The technical representative knew of Loctite application in the medical field for use in devices that must undergo radiation sterilization. Loctite 4014 is also similar in viscosity to 420 and can handle high

temperature (80 °C). The Loctite 4014 data sheet appears to imply that Loctite has test data for 4014 showing only small degradation to 7 Mrads. A careful reading of the datasheet leaves some doubt that data for 4014 is the actual material data being reported. Nevertheless, 4014 is the chosen substitute. Dr. Jim Sutter is a materials chemist researcher at Glenn and very familiar with the commercial materials community. He provided some in-depth investigation of Loctite. Dr. Sutter identified through contacts with technical representatives at Loctite that the 4014 glass transition temperature is near that of 420, 120 °C<sup>3</sup>.

Tra-Con Tra-Bond F113 was a material initially considered as a candidate replacement for Loctite 420, based on recommendation of experts at GE-Schenectady. After NASA obtained a copy of the technical data sheet from Tra-Con, the glass transition temperature was found to be too low for our application, 45°C.

## **6. EC 2216 Gray**

The materials used at three locations were replaced with EC2216, a material commonly used in JPL spacecraft in high radiation environments and one specifically recommended in Reference 4. The application is a little higher temperature than used in JPL spacecraft, so some investigation as to the adequacy for the Stirling application on the part of a NASA Glenn materials expert was undertaken. Dr. Jim Sutter is a materials chemist researcher at Glenn and very familiar with the commercial materials community. He provided some in-depth investigation of EC2216.

### **6.1. EC 2216 to replace Dolph CD-1057 Epoxy and Permabond 919, 920 on the stator coils**

Dolph CD-1057 Epoxy is a two-part epoxy used on the stator coils. A layer of Dolph CD-1057 is applied over the coils, which are square copper wires. It covers the coils, holds the coils together, has a glassy, varnish-like appearance, and is brittle. Because there was no radiation testing data from the manufacturer, the decision to substitute this epoxy with EC2216 was made. EC2216 is on the JPL recommended list for adhesives for the Outer Planet/Solar Probe project. However, specific radiation testing data is not available. STC also used another adhesive for this same purpose, Permabond 919 and 920. Both are being replaced by EC2216. Permabond also has no data on radiation hardness. The adhesive is actually called "Powerbond." It requires a secondary cure at a high temperature to get the cross-linking for high temperature capability. STC did not do this secondary cure when they used it for the coil windings. EC2216 does not require a secondary cure for its high radiation tolerant properties. In the initial efforts with the 2216, STC found it to be more pliable than the Dolph or Permabond. This was confirmed by Dr. Sutter. STC also tested a coil bonded with 2216 in a furnace at 100 °C. Based on pulling on the coil, the 2216 strength appeared to be acceptable to STC. This will be further evaluated during testing of the TDC's 5/6 at STC and NASA GRC.

## **6.2. EC2216 to replace Scotch-weld DP-460 on the stator magnets/laminations bond and stator lamination/bobbin bond**

Scotchweld DP-460 is used to bond the stator magnet to the laminations, and to bond the bobbin to the laminations. The bobbin is a center core of plastic material around which the coils are wound. No radiation data was available. The 3M technical representative was contacted to suggest a substitute, and she suggested 3M-EC2216. This is used in the terrestrial nuclear power industry, according to 3M. The shear strength for DP-460 is higher than for 2216 at the operating temperature (700 psi versus 400 psi lap shear at 82 °C). Both degrade with temperature.

## **6.3. Dexter Hysol as an Alternative to 2216**

NASA asked Schaeffer Magnetics to help with a recommendation for a wicking adhesive typically used for electric motor coils for space application. Schaeffer Magnetics is a company known for supplying electric motors used in satellites for defense, commercial, and NASA missions. The company revealed they use Dexter Hysol EA 9396 on some coils in their space-rated motors. However, the glass transition temperature was reported to be only 76 °C by the Dexter Hysol tech rep. This may not be adequate for our slightly higher temperature application, where the alternator magnets may operate near 80 °C. Dexter Hysol was not recommended for this application. The data sheet is not available electronically, but is available via FAX at 925-458-8030.

## **7. 3M Heat Shrink Tubing**

Heat shrink tubing currently used will be replaced with tubing made of Kynar, which is PVDF, polyvinylidene fluoride. PVDF is identified in reference 1 as incipient to mild damage to almost  $10^7$  Rads. This agrees with JPL information, which reports PVDF hard to 500 Mrads or better.

## **8. Garolite G-10**

This is an epoxy-glass laminate. Reference 1, page 25, reports that epoxy glass laminate is capable of withstanding  $10^8$  Rads.

## **9. TFE Wire Insulation**

Teflon cannot withstand even low levels of ionizing radiation. The Teflon must be replaced. PVDF is a common alternative for wire insulation. PVDF, polyvinylidene fluoride, is identified in reference 1, page 9, as incipient to mild damage to almost  $10^7$  Rads. This agrees with JPL information, which reports PVDF hard to 500 Mrads or better.



## **10. TFE Structure**

Teflon is used for the bumper on the end of the piston. This will be replaced with PVDF. A careful machining process is necessary to form the proper shape at the piston face.

## **11. Summary Recommendation**

In the Fall of 1999, several critical issues were identified as possible “show-stoppers” for the application of a Stirling convertor to an advanced radioisotope power source. This investigation has shown that a list of suitable organic material replacements has been found, and that there are no “show-stoppers.” Interested parties should be aware of upcoming functional testing of additional baseline 55 We Stirling convertor units. These additional units will be the first time the replacement organics are used in a Stirling convertor. No issues are expected. At the time of this report, the testing will take place in CY 2000 at NASA Glenn Research Center and at STC.

A note about the nuclear fuel radiation is warranted. The radiation produced by the nuclear fuel was considered negligible with respect to damaging the organics inside the convertor, in comparison to the environmental radiation. This should be re-visited when the final SRPS design integration concept is available. The distance of the organics from the GPHS modules is one of the key parameters. It is expected that, in any design, the nuclear fuel radiation will always be negligible when compared to the Europa environment radiation.

Some mention of environmental radiation dose calculations is needed. Interested parties should probably take a fresh-look at the necessity of dose calculations when a final SRPS concept becomes available. There were no computer calculations performed for dose estimates in the organics for this investigation. As a guideline, the estimated ionizing dose in Silicon of 4 Mrads behind 100 mils aluminum shielding was used. Radiation deposited in the material Silicon is a typical ionizing radiation calculation performed, because most ionizing radiation damage assessments are interested in survivability of electronics. It is possible that the dose in the various organics may be different for the same ionizing radiation source. The difference from Silicon is thought to be negligible for the scope of this report. The flight unit Stirling Convertor pressure vessel is anticipated to be stainless steel or titanium with wall thickness near 60 mils. However, there is very high confidence that the intrinsic radiation shielding provided by the final design of the pressure vessel, as is the case with the current design, will exceed that of an equivalent design provided by 100 mils of aluminum. Therefore, the total dose of 4 Mrads is reasonably conservative for this level of investigation. Two further points to mention which may decrease conservatism. First, computer ray-tracing modeling considering the real geometry and the additional shielding of various structural metallic and non-organic parts inside the convertor will probably show a lower dose than 4 Mrads. Second, consideration of the radiation spectra near Europa may show less damaging effects than a

Total Ionizing Dose (TID) of 4 Mrads, although total dose methods were considered adequate for organics at this level of investigation.

Magnet radiation hardness is not an issue. As pointed out in the summary presentation in Section 2 of this report, a very great deal of margin exists, and no further investigation is recommended.

Radiation testing was not mentioned in this report, but is always a consideration for radiation hardness verification. The decision to perform radiation testing on individual materials or to perform radiation testing on the convertor at the unit level should be made later, in concert with the entire spacecraft radiation control plan. There are considerations of radiation design margin (RDM), which may be different for organics than for electronics. Although it appears no radiation testing is needed on the Stirling convertor organics nor on the convertor at the unit level, a fresh-look study on this matter is warranted in future months. JPL, as the overall spacecraft integrator, is expected to further refine requirements for spacecraft level and unit level radiation hardness for all materials and electronics aboard the spacecraft.

## **12. References**

1. Hanks, C. L., and Hamman, D. J., Radiation Effects Design Handbook, Section 3. Electrical Insulating Materials and Capacitors, NASA CR-1787, Prepared for the Radiation Effects Information Center, Battelle Memorial Institute, Columbus, Ohio, July 1971.
2. JPL, Outer Planet/Solar Probe Review, Veteran's Day, November 12, 1999.
3. Conner, J. to Sutter, J., Loctite to NASA GRC, Personal Communication, February 11, 2000.
4. Willis, P. B., JPL, "X-2000 Mission Materials Radiation Effects," presentation to X-2000 Project, May 26, 1998.



**13. Material Data Sheets and Other Ancillary Information**

**Loctite Data Sheets .....12**

**Loctite to GRC Personal Communication (Reference 3).....13**

**Permabond Data Sheets.....14**

**Dolph Data Sheets.....15**

**3M Corporation EC2216 Data Sheets.....16**

**Dexter Data Sheets.....17**

**JPL Radiation Effects Information.....18**

**Tra-Con Data Sheet.....19**

**JPL X-2000 Presentation Excerpt (Reference 4).....20**

**Excerpt from Reference 1 (Fundamental Radiation Guidelines).....21**

**Excerpts from Reference 2 (JPL Requirements).....22**



## **Loctite Product Data Sheets**



### **Reference 3 (Loctite to GRC Communication)**



## **Permabond Data Sheets**



## **Dolph Data Sheets**



## **EC2216 Gray Data Sheets**





## **Dexter Data Sheets**



## **JPL Spacecraft Radiation Effects Information**



## **Tra-con Data Sheet**



#### **Excerpts of Reference 4 (JPL Radiation Information)**



**Page 9 of Reference 1 (Fundamental Guidelines)**



### **Excerpts from Reference 2 (JPL Requirements)**